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THE PEAK ENERGY DISTRIBUTION OF THE νF_ν SPECTRA AND THE IMPLICATIONS FOR THE JET STRUCTURE MODELS OF GAMMA-RAY BURSTS

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ABSTRACT

We study the peak energy (E_p) distribution of the νF_ν spectra of gamma-ray bursts (GRBs) and X-ray flashes (XRFs) with a sample of 57 bursts observed by *High Energy Transient Explorer* (*HETE-2*) French Gamma Telescope and discuss its implications for the jet structure models. Combining the observed E_p distribution of *HETE-2* GRBs/XRFs with that of BATSE GRBs, we find that the observed E_p distribution of GRBs/XRFs is a bimodal one with peaks of $\lesssim$30 keV and ~160–250 keV. According to the recently discovered equivalent-isotropic energy–E_p relationship, such a bimodal distribution implies a two-component structure of GRB/XRF jets. A simple simulation analysis shows that this structured jet model does roughly reproduce a bimodal distribution with peaks of ~15 and ~200 keV. We argue that future observations of the peak of ~15 keV in the E_p distribution would be evidence supporting this model. *Swift*, which covers an energy band of 0.2–150 keV, is expected to provide a key test for our results.

Subject headings: gamma rays: bursts — gamma rays: observations — ISM: jets and outflows — methods: statistical

1. INTRODUCTION

X-ray flashes (XRFs) have been getting a lot of attention in the last 2 years (Heise et al. 2001; Kippen et al. 2003). They are thought to be a lower energy extension of the known gamma-ray burst (GRB) population, based on the fact that their spectral behaviors are similar to those of GRBs (Kippen et al. 2003; Barraud et al. 2003; Sakamoto et al. 2004; Lamb et al. 2003a, 2003b, 2004). The nature of a narrow cluster of the observed E_p distribution of BATSE GRBs remains poorly understood but might be related to the jet structure of GRBs. XRFs broaden the energy coverage of prompt GRB emission and may bring more signatures of the jet structure of GRBs (Lamb et al. 2003a, 2003b, 2004).

The jet structure models are currently under heavy debate. Any model should present a unified description for GRBs and XRFs. Two currently competing models are the structured jet model (Mészáros et al. 1998; Dai & Gou 2001; Rossi et al. 2002; Zhang & Mészáros 2002; Granot & Kumar 2003; Kumar & Granot 2003; Panaitescu & Kumar 2003; Wei & Jin 2003) and the uniform model (e.g., Rhoads 1999; Frail et al. 2001). Zhang et al. (2004a) show that the current GRB/XRF prompt emission/afterglow data can be described by a quasi-Gaussian–type (or similar structure) structured jet with a typical opening angle of ~6° and with a standard jet energy of ~10^{51} ergs. Alternatively, based on the *High Energy Transient Explorer 2* (*HETE- 2*) observations, Lamb et al. (2003a, 2003b, 2004) propose that the uniform jet model can reasonably describe the unified scheme of GRBs/XRFs. Very recently, the two-component jet model was advocated by Berger et al. (2003b) based on observations of GRB 030329, which has two different jet breaks in an early optical afterglow light curve (0.55 days; Price et al. 2003) and in a late radio light curve (9.8 days). Millimeter observations of this burst further support the two-component jet model (Sheth et al. 2003). Numerical calculations of such a model were performed by Huang et al. (2004). This model suggests that a GRB/XRF jet has two components: a narrow, highly relativistic one and a wide, mildly relativistic one. When the line of sight of an observer is within the narrow component, the observed burst is a typical GRB, but when the line of sight is pointing to the wide component, it is an XRF.

A broad spectral energy distribution could constrain the jet structure models. A low peak energy of the νF_ν spectrum ($E_p < 50$ keV) and weak gamma-ray fluxes ($F < 0.2$ photons cm^{-2} s^{-1}, 50–300 keV energy range) distinguish XRFs from typical GRBs (Kippen et al. 2003; Mochkovitch et al. 2003). It is well known that the observed E_p distribution of BATSE GRBs is narrowly clustered. Does the observed E_p distribution of XRFs exhibit a similar feature? In this Letter, we focus on this question. We analyze the observed E_p distribution with a sample of 57 bursts observed by the *HETE-2* French Gamma Telescope (FREGATE). Combining the observed E_p distribution of *HETE-2* GRBs/XRFs with that of BATSE GRBs, we find that the observed E_p distribution of GRBs/XRFs is a bimodal one peaking at $\lesssim$30 keV and ~160–250 keV. With respect to this result, we suggest that the two-component jet model is a reasonable candidate model for GRB/XRF jets. A simulation analysis confirms this suggestion.

2. DISTRIBUTION OF E_p

We make a search for the *HETE-2* GRBs/XRFs reported in the literature and on the *HETE -2* Web site.[4] All the bursts with E_p or fluences (S) in the available energy bands of 7–30 and 30–400 keV are included in our sample. We obtain a sample that includes 57 bursts. Among them, 49 of the bursts are taken from Barraud et al. (2003), Atteia (2003), Sakamoto et al. (2004), Lamb et al. (2003a, 3003b, 2004), and the *HETE-2* Web site. Their E_p values are derived from spectral fittings. Please note that the E_p values of GRB 010923, 011216, and 021004 presented in Barraud et al. (2003) are incorrect, and they are taken from Lamb et al. (2003a, 2003b, 2004). For the other eight bursts, GRB 030824, 030823, 030725, 030913, 030528, 030519, 030418, and 030416, only fluences in the

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[4] See http://space.mit.edu/HETE/Bursts.

energy bands of 7–30 and 30–400 keV are available. For these bursts, we estimate their E_p by their spectral hardness ratios, which are defined as $R = S_{30\text{–}400\ \mathrm{keV}}/S_{7\text{–}30\ \mathrm{keV}}$. Since the spectra of GRBs/XRFs can be well fitted by the Band function (Band et al. 1993) with similar spectral indices (Kippen et al. 2003; Barraud et al. 2003), their E_p should be proportional to R. A best fit to the data presented in Barraud et al. (2003) derives $\log E_p = (1.52 \pm 0.05) + (0.92 \pm 0.07) \log R$ with a linear coefficient of 0.93 and a chance probability $p < 0.0001$ ($N = 32$, without considering GRB 010923, 011216, or 021004). We thus estimate the E_p values of the above eight bursts by using this relation.

We show the E_p distribution in a range of $\log E_p/\mathrm{keV} = 0.6$–3.0 with a step of 0.23 for these bursts in Figure 1*a*. It is found that the distribution has three peaks at 30, 160, and 450 keV. We note that the peaks of 160 and 450 keV seem to be embedded in one peak, and the gap at $E_p = 275$ keV is likely to be fake. The spectral analysis for a bright BATSE GRB sample by Preece et al. (2000) has shown that the E_p values are clustered at 100–1000 keV with a peak of ~250 keV (the dashed line in Fig. 1*a*). We thus suspect that the peaks of 160 and 450 keV are likely to be embedded in one peak, which is similar to that of the BATSE GRB sample. If the case really shows one peak, the E_p distributions observed by *HETE- 2* and by BATSE in the range of 100–1000 keV should be consistent. We examine this hypothesis using a Kolmogorov-Smirnoff (K-S) test (Press et al. 1997, p. 617). The result of the K-S test is described by a statistic of $P_{\text{K-S}}$: a small value of $P_{\text{K-S}}$ indicates a significant difference between two distributions ($P_{\text{K-S}} = 1$ indicates that two distributions are identical, and $P_{\text{K-S}} < 0.0001$ suggests that the consistency of two distributions should be rejected; e.g., Bloom 2003). We obtain $P_{\text{K-S}} = 0.22$, indicating that the consistency of the two distributions is acceptable. However, their difference is still quite significant. This difference might be due to a strong sample selection effect in the BATSE GRB sample presented by Preece et al. (2000), who considered only those bursts with total fluence $\geq 5 \times 10^{-5}$ ergs cm^{-2} or peak fluxes higher than 10 photons cm^{-2} s^{-1} in a 1.024 s timescale. To avoid such a sample selection effect, we further compare the distributions of the hardness ratios of *HETE -2* bursts and BATSE bursts in Figure 1*b*. In Figure 1*b*, the BATSE GRB sample includes all of the long-duration bursts without any sample selection effect (1213 events, from the BATSE Current Catalog). A K-S test of the two distributions in the range of $\log R = 0.3$–1.5 derives $P_{\text{K-S}} = 0.95$, strongly suggesting a consistency between the two distributions in that range. Thus, we suggest that the E_p distribution in 100–1000 keV should form one sole peak, centered at ~160–250 keV.

The peak of $E_p \sim 30$ keV or $R \sim 1$ seems to be a unique one. A sharp cutoff occurs on its left side. This might be caused by the limit of *HETE- 2*. Hence, we suggest that the E_p distribution should exhibit another peak of an energy $\lesssim 30$ keV. Based on the above analysis, we propose that the E_p distribution of GRBs/XRFs is a bimodal one, peaking at an energy $\lesssim 30$ keV and ~160–250 keV.

3. IMPLICATIONS FOR THE JET STRUCTURE AND UNIFIED MODELS OF GRBs/XRFs

The observed bimodal distribution of E_p for GRBs/XRFs might strongly constrain the jet structure models of GRBs/XRFs. From $E_{\mathrm{iso},52} \simeq [E_{p,2}(1+z)]^2$, where $E_{\mathrm{iso},52} = E_{\mathrm{iso}}/10^{52}$ ergs and $E_{p,2} = E_p/10^2$ keV (Amati et al. 2002; Lloyd-Ronning & Ramirez-Ruiz 2002; Atteia 2003; Yonetoku et al. 2004; Sakamoto et al. 2004; Lamb et al. 2003a, 2003b, 2004; Liang et al. 2004), and $E_{\mathrm{iso},52}(1 - \cos\theta_j) = 0.133$, where θ_j is the jet opening angle (Frail et al. 2001; Panaitescu & Kumar 2001; Piran et al. 2001; Bloom et al. 2003; Berger et al. 2003a), we can derive

$$\theta_{\mathrm{j}} = \arccos\left\{1 - \frac{0.133}{[E_{p,2}(1+z)]^2}\right\}. \quad (1)$$

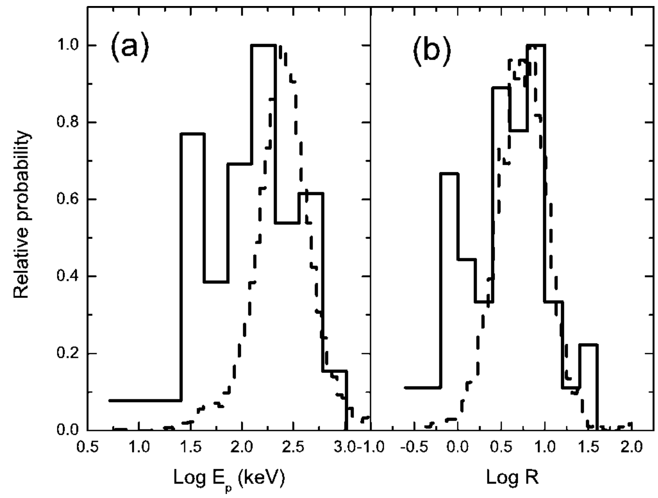

FIG. 1.—Observed (*a*) E_p and (*b*) hardness ratio distributions of *HETE -2*/FREGATE GRBs/XRFs. In panel *a*, the dashed line is the observed E_p distribution of a bright BATSE GRB sample taken from Preece et al. (2000). In panel *b*, the dashed line is the observed hardness ratio distribution of all long-duration BATSE GRBs without any sample selection effect (from BATSE Current Catalog).

In the uniform jet model, one expects that both XRFs and GRBs should obey equation (1). However, this relation cannot simply extend to any bursts with $E_p(1+z) < 35$ keV because of the limit of $\theta_j < \pi/2$. The redshifts of the two extremely soft XRFs, GRB 020903 and 030723, are 0.251 (Soderberg et al. 2003) and less than 2.1 (Fynbo et al. 2004), respectively, but their E_p values are less than 20 keV. The two XRFs violate this relationship. In addition, the uniform jet model may not accommodate the observed bimodal distribution of E_p.

A quasi-universal Gaussian-type jet model may also present a unified picture for GRBs/XRFs. Lloyd-Ronning et al. (2004) found that this model can reproduce the relation of the equivalent-isotropic energy to the viewing angle, and Zhang et al. (2004a) further showed that the current GRB/XRF prompt emission/afterglow data can be described by this model (or similarly structured jet) with a typical opening angle of ~6° and with a standard jet energy of ~10^{51} ergs. However, the observed bimodal distribution of E_p is difficult to explain using this model.

According to the equivalent-isotropic energy–E_p relationship discovered recently by Amati et al. (2002), the bimodal E_p distribution seems to imply a two-component structure of GRB/XRF jets. To investigate whether or not this model can reproduce the observed bimodal distribution of E_p, we make a simple simulation analysis. We describe the energy per solid angle of the two-component model by two Gaussian jets,

$$\epsilon = \epsilon_0 (e^{-\theta_v^2/2\theta_1^2} + \mu e^{-\theta_v^2/2\theta_2^2}), \quad (2)$$

where θ_v is the viewing angle measured from the jet axis, ϵ_0

is the maximum value of energy per solid angle, μ is the ratio of $E_{\rm iso}$ in the wide component to narrow component, and θ_1 and θ_2 are characteristic angular widths of the narrow and wide components, respectively. Since $E_p \propto \epsilon^{0.5}$, the observed E_p should be given by

$$E_p = E_{p,0}(1+z)(e^{-\theta_v^2/2\theta_1^2} + \mu e^{-\theta_v^2/2\theta_2^2})^{1/2}. \qquad (3)$$

Similar to Lloyd-Ronning et al. (2004) and Zhang et al. (2004a), we assume that the two components are quasi-universal, where "quasi" means that the parameters of this model have a dispersion but are not invariable. We perform a simple Monte Carlo simulation analysis with the distributions of these parameters. The probability of observing a GRB/XRF with θ_v is proportional to $\sin\theta_v$. One can expect this probability to be random. Thus, we assume that $\sin\theta_v$ is uniformly distributed in the range of 0–1. The $E_{p,0}$ distribution should be mainly determined by a bright GRB sample. Since the observed E_p for bright BATSE GRBs are narrowly clustered at 200–400 keV and since the measured redshift distribution is around 1, we take the differential distribution of $E_{p,0}$ as that of E_p for the bright GRBs, but centered at $\log E_{p,0} = 2.80$ (i.e., $E_{p,0} = 630$ keV), which is given by $w(\log E_{p,0}) = 0.018 \exp\{-2[(\log E_{p,0} - 2.80)^2/0.45^2]\}$, where the coefficient 0.018 is a normalized constant. We assume that the redshift distribution is the same as the one of Bloom (2003), who assumed that the burst rate as a function of redshift is proportional to the star formation rate and who presented the observed redshift distribution incorporating observational biases (model SF1 from Porciani & Madau 2001 is used in this work). We also restrict $z \leq 4.5$ because the largest z is 4.5 in our present GRB sample. For θ_1 and μ, we cannot reasonably model their distributions with the present data, and thus we simply estimate their values as follows. Since the mean value of the jet opening angles of 16 GRBs presented in Bloom et al. (2003) is ~0.15 rad (without considering the eight GRBs whose limits of jet opening angles are presented), we take $\theta_1 \sim 0.15$ rad. Based on the results shown in Figure 1, we have $\mu = E_{\rm iso,\,XRF}/E_{\rm iso,\,GRB} \simeq 10^{-1.7}$. The θ_2 is the most poorly understood among these parameters. We let it be an adjustable variable with a limit of $\theta_2 > \theta_1$. In our simulation analysis, we take $\theta_2 = 0.32$ rad (see below).

We simulate a sample of 10^5 GRBs/XRFs. Our simulation analysis procedure is described as follows. To derive a value of parameter x for a given burst (x is one of $E_{p,0}$, z, and θ_v), we first derive the accumulative probability distributions of these parameters $P(x)$ $(0 < P(x) \leq 1)$, then generate a random number m $(0 < m \leq 1)$, and finally obtain the value of x from the inverse function of $P(x) = m$; i.e., $x = P^{-1}(m)$. The values of θ_1 and μ are fixed at 0.15 rad and $10^{-1.7}$, respectively. The value of θ_2 is an adjustable variable with a limit of $\theta_2 > \theta_1$. We find that $\theta_2 = 0.32$ rad can roughly reproduce the E_p distribution shown in Figure 1. We calculate the E_p for each simulated GRB/XRF with the above parameters using equation (3). The E_p distribution is shown in Figure 2. We find that the distribution is bimodal with peaks of ~15 and ~200 keV and with a valley at ~50 keV. These results show that the two-Gaussian jet model can roughly reproduce the bimodal distribution of the observed E_p.

In our simulation, we do not consider any instrument threshold setting. The energy bandpass of *HETE-2*/FREGATE is 7–400 keV. From Figure 1, we find a sharp cutoff at $\log E_p/{\rm keV} = 1.3$ (i.e., $E_p = 20$ keV), which is close to the lowest end of the *HETE -2* energy bandpass. This E_p value might reflect the effective threshold of *HETE -2*. We roughly estimate the ratio of observable GRBs to XRFs for *HETE-2* with this threshold in our simulation analysis, and we find that this ratio is about 2.2 : 1. This is in good agreement with *HETE -2*/FREGATE observations (39 *HETE -2* GRBs and 18 XRFs in the *HETE -2*/FREGATE sample).

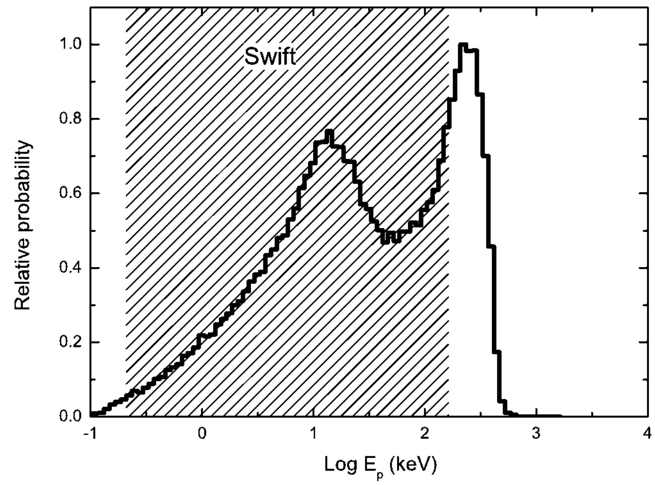

FIG. 2.—Simulated E_p distribution of the two–quasi-universal Gaussian jet model. The diagonal line region is the energy band of *Swift*.

4. CONCLUSIONS AND DISCUSSION

We have studied the observed E_p distribution of 57 *HETE-2*/FREGATE bursts and discuss its implications for the jet structure models. Combining the observed E_p distribution of *HETE-2* GRBs/XRFs with that of BATSE GRBs, we suggest that the observed E_p distribution of GRBs/XRFs is bimodal with peaks of $\lesssim$30 keV/~160–250 keV. According to the recently discovered equivalent-isotropic energy–E_p relationship, we find that the bimodal distribution can be explained by the two-component model of GRB/XRF jets. A simple simulation analysis shows that this structured jet model does roughly reproduce the bimodal distribution with peaks of ~15 and ~200 keV.

The peak of ~15 keV in the simulated E_p distribution is key evidence for the two-component jet model. It is near the lowest end of the energy bandpass of *HETE -2*/FREGATE. Fortunately, *HETE -2* provides a weak clue to this peak. A more sensitive instrument than *HETE-2* with an energy bandpass of 1–50 keV is required to further confirm this peak. *Swift*, which covers an energy band of 0.2–150 keV (we mark this region in Fig. 2 with diagonal lines) is expected to provide a key test for it.[5]

Simulations of the propagation and eruption of relativistic jets in massive Wolf-Rayet stars by Zhang et al. (2004b) show that an erupting jet has a highly relativistic, strongly collimated core and a moderately relativistic, less energetic cocoon. The cocoon expands and becomes visible at larger angles. The energy ratio of the cocoon to the core in their simulation is about 1 order. From our simulation results, we find that it is $\sim(E_{p,\,\rm GRB}/E_{p,\,\rm XRF})^2(\theta_1/\theta_2)^2 \sim 40$, being roughly consistent with their results. Their simulations seem to support the two-component jet model. We have noted that the ability of the cocoon to cause an XRF depends sensitively on its Lorentz factor, which is determined by the degree of mixing between

[5] See http://swift.gsfc.nasa.gov/science/instruments.

the jet and envelope material. Matzner (2003) argued that this mixing might be difficult to resolve in numerical simulations.

A two-component jet was suggested to be universal for GRB/XRF phenomena in this Letter, based on the multiwavelength observations of GRB 0303029 (Berger et al. 2003b; Sheth et al. 2003) and the bimodal distribution of E_p. It should be pointed out that other jet models such as uniform jets and single-component universal jets were proposed to explain numerous observations on the afterglows and some correlations (e.g., Lamb et al. 2003b; Lloyd-Ronning et al. 2004; Lloyd-Ronning & Zhang 2004). Thus, one would expect strong evidence showing which jet model is more reasonable.

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